The Theory and Simulation of Relativistic Jet Formation: Towards a Unified Model For Micro- and Macroquasars

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I review recent progress in the theory of relativistic jet production, with special emphasis on unifying black hole sources of stellar and supermassive size. Observations of both classes of objects, as well as theoretical considerations, indicate that such jets may be launched with a spine/sheath flow structure, having a much higher Lorentz factor (~ 50) near the axis and a lower speed ($\Gamma \sim 10$ or so) away from the axis. It has become clear that one can no longer consider models of accretion flows without also considering the production of a jet by that flow. Furthermore, the rotation rate of the black hole also must be taken into account. It provides a third parameter that should break the mass/accretion rate degeneracy and perhaps explain why some sources are radio loud and some radio quiet.

Slow jet acceleration and collimation is expected theoretically, and can explain some of the observed features of AGN jet sources. Finally, relativistic jets launched by MHD/ED processes are Poynting flux dominated by nature, and are potentially unstable if there is significant entrainment of thermal material.

1. The Launching of Relativistic Jets

As this meeting comes only a few months after the meeting on microquasars in Cargese, Corsica, my presentation here will be similar to that given in Cargese, but with a more general approach to *all* relativistic jet sources — Microquasars and Macroquasars alike. This paper, therefore, will be an extension and update of the Cargese paper [15], and the reader will be referred to the latter rather frequently.

1.1. Relativistic Jet Sources and their Speeds

The first point that I wish to make is that, *in attempting to understand the launching, acceleration, and collimation of relativistic jets, high energy jetted sources of all types should be considered.* Their similarities point to closely-related mechanisms and similar physics, and their differences give clues on how the general mechanism might operate differently under different conditions.

Microquasars. This class of objects has historically included Galactic jet sources, mainly low-mass X-ray binaries (LMXBs) like GRS 1915+105 and other objects like SS433 (which may be a neutron star). Recently, HMXBs like Cyg X-1 have been found to produce jets and, therefore, added to the class, and γ-ray bursts (GRBs) are treated as a closely-related object. However, now that Z and atoll neutron star binaries, isolated pulsars, and even core-collapse supernovae appear to produce jetted flows, I have suggested that the Microquasar class now include *all* objects of stellar mass that produce relativistic collimated flows. As discussed in [15], these objects are related not only in their phenomenology and in their underlying jet-production mechanism, but also in their common origin as the last stages in the evolution of massive stars.

Macroquasars. Like the term 'microquasar', the term 'quasar' has evolved — from the early meaning of quasi-stellar *radio* source, to encompassing any extragalactic object (radio loud or quiet) whose host galaxy is difficult to detect. To the Macroquasar class I also suggest adding the active galactic nuclei (AGN) objects — radio galaxies and Seyfert galaxies — which are distinguished from the others only by the faintness of their central optical source relative to the brightness of the surrounding galaxy.

The recent observations of Blundell & Rawlings [4] are extremely important in any attempt to unify all AGN and quasars. These authors found the first Fanaroff& Riley class I radio quasar, which had been known previously as a radio 'quiet' quasar. Its radio luminosity is just below the FR I/FR II break ($\sim 10^{41}$erg s^{-1}), or about ten times more powerful than Centaurus A. While much more work needs to be done, the implication is that many, if not all, radio 'quiet' quasars are actually giant radio galaxies, appearing much like Centaurus A, but with a very bright optical core at the center of the nucleus.

While I have suggested that Microquasars be unified on the basis of an evolutionary scheme [15], it is more appropriate to unify Macroquasars on the basis of the size, fueling rate, and spin of their central black hole (in addition to the jet viewing angle) using, for example, theoretical Owen-Ledlow diagrams of the radio-optical plane. Figure 1 shows such a scheme, slightly modified from that presented in [13]. Except for the low-mass cutoffs of the FR II objects, the lines are *computed* from accretion and jet-production equations, not simply drawn schematically. Note that this grand unified scheme predicts that there are substantial FR I quasars and that their class merges into the radio quiet quasar class, as suggested by recent observations [4].

Jet Speeds. Measured jet speeds in the above sources range from ~ 0.5 c in the neutron star sources, to Lorentz factors of $\Gamma \sim 10$ in Micro- and Macroquasar black hole systems, to $\Gamma > 100$ in the GRBs. Current collapsar models of long-duration GRBs suggest that the actual jet speed produced by the black hole itself may be only of order $\Gamma < 50$, with the additional acceleration to Γ of several hundred being provided by a confining supernova envelope and the subsequent breakout [23]. (If this is the case, then one might expect short-duration GRBs to have Lorentz factors significantly under 100, as they are thought to be associated with neutron star mergers and therefore not occurring inside dense envelopes.)

Broad absorption line (BAL) quasars represent another type of outflow that may be related to jets. Because their P-Cygni lines imply low filling factors in the flow, and because of the existence of detached absorption troughs, there is some reason for believing that the flow may be bi-polar and limb-brightened in nature. Their velocities of ~ 0.1 c are considerably slower than typical jet speeds, and radiation pressure may play a key role here in the initial launching. Nevertheless, it is possible that magnetic effects like those discussed below are still at work in these outflows, shaping them and perhaps providing additional acceleration far from the disk.

1.2. Of Spines and Sheaths

The second point that I wish to make is that *there is some observational evidence that the same source may produce jets of rather different Lorentz factors*, either simultaneously or when the source is in different accretion states. First of all, there has been considerable discussion of the spine-sheath model at this conference (see, *e.g.*, reference [6]). In addition, I offer two other examples. Intra-day variable (IDV) sources such as PKS 0405-385 [19] show evidence of Lorentz factors of up to 75, even when the interstellar scintillation model is applied to the variability. When this Jansky-level core is de-boosted, one derives only a microjansky-level intrinsic flux for this very relativistic flow. However, for the surrounding centimeter flux, with a typical Lorentz factor of 5-10, the de-boosted flux is at the millijansky level — three orders of magnitude stronger. The implication is that a great many sources may be producing very relativistic 'spine' jet flows that normally are not seen because of their weak microjansky-level flux and their highly-beamed nature.

Another clue may be in the behavior and spectrum of Cyg X-1. Like most Microquasars, the source produces a steady jet when it goes into the low/hard state [5]. The non-thermal power-law tail in the hard X-ray region in such sources has been suggested to come from close to the base of the jet itself [11]. In the high/soft state, Cyg X-1 does not produce a detectable radio jet, yet the γ-ray spectrum has a power-law tail that extends out to several MeV! Clearly, there is still substantial non-thermal activity in what would otherwise appear to be a rather thermal and soft source. While the role of this very hard emission

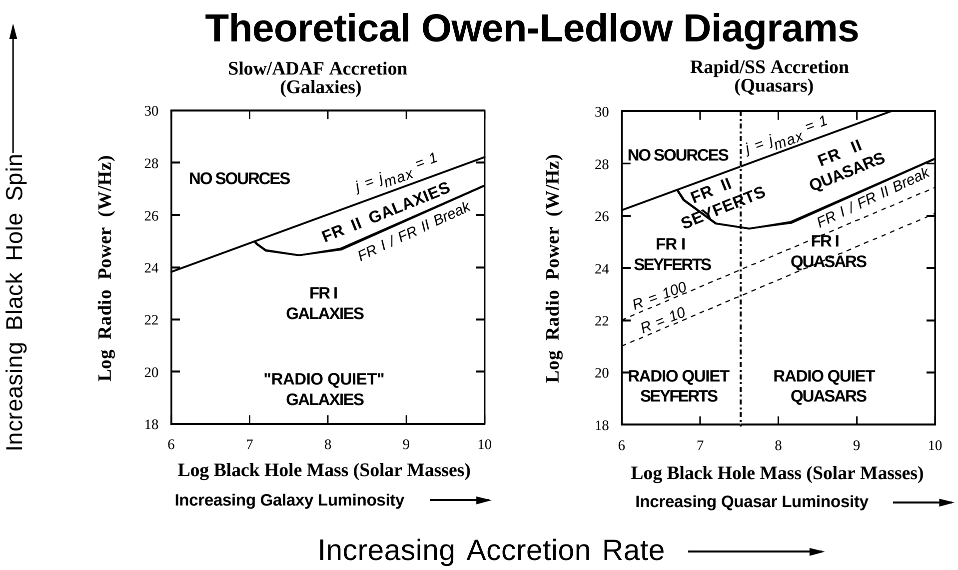

Figure 1. Grand unified scheme for Macroquasars, beyond viewing angle considerations (after [13]). Diagrams were *computed* from accretion and jet-production equations. The upper boundary is essentially equation (1) with $\dot{M}/\dot{M}_{Edd} = j = 1$. Note the dotted lines of constant radio-to-optical flux ratio ($R = 10, 100$) and that the FR I quasar region occupies the traditional 'radio quiet' quasar region.

is unclear at this point, it is interesting to speculate that the γ-ray tail may indicate the production of a weak, but very high Lorentz factor jet at the center of the otherwise thermal disk — a spine for the low/hard state radio jet sheath.

1.3. Jet Launching Mechanisms

As discussed by [1,14,15] the current popular model for launching, accelerating, and collimating astrophysical jets is a magnetohydrodynamical/electrodynamical one. A strong electromagnetic field in the central engine, coupled with differential rotation, serves to convert rotational kinetic energy into kinetic energy of outflow. A magnetic pressure gradient (plus, perhaps, the action of thermal and/or radiation pressure) lifts the material out of the gravitational potential well, and the pinch effect (hoop stress of the magnetic field coiled by the rotation) collimates the outflow into a jet.

The above basic mechanism can be realized in a variety of Micro- and Macroquasar situations. For neutron star systems, the magnetic field and rotation of the pulsar or protopulsar will accelerate plasma trapped in the magnetic field lines. (This plasma can originate from either particle creation in spark gaps or accretion flows.) Ejection of a collimated outflow at roughly the neutron star escape speed ($\sim 0.5\ c$) provides a natural explanation for pulsar and supernova jets, and even possibly SS433-type objects.

In systems with substantial accretion disks the combination of orbital motion and a disk coronal magnetic field can provide a similar mechanism, first proposed by Blandford and Payne (BP) [2]. Such accretion disk MHD winds could operate in both accreting neutron star and black hole systems.

Finally, in black hole systems the magnetic field can extract rotational energy of the black hole in two different ways. The first method, suggested by Punsly and Coroniti [18], is really an extension of the BP mechanism to accretion systems that are significantly affected by frame dragging. Rotation of the space near the black hole, if in the same sense as the disk, enhances the disk MHD wind power. The coupling to the black hole rotation is indirect, through material that is accelerated into *negative energy orbits* inside the ergo-

sphere. When accreted by the hole, this material *spins down the hole* in a magnetic Penrose-type process. The second method, suggested by Blandford and Znajek (BZ) [3], utilizes direct magnetic coupling with a field that threads the horizon and either the accretion disk or an outflowing wind, much like the structure of a pulsar wind.

The third point I would like to make, then, is that *there are natural theoretical reasons for believing that more than one MHD jet launching mechanism may be at work in Micro- and Macroquasars*, and that there are definite candidates in the different cases. The following identifications are suggested, although the set is certainly subject to change as more is learned about these sources. BP-type outflows may be responsible for the lower velocity ($\sim 0.1\ c$) outflows in black hole systems, shaping them if not also accelerating them. The PC/BP mechanism inside the ergosphere may be responsible for most jets we see in AGN, quasars, and classical microquasars. Lorentz factors of 3 have been achieved in simulations of this process [8], and values of 10 or more are not unexpected from a region where the metric 'rotational velocity' is formally greater than c. Finally, it is tempting to identify the very high Lorentz factor (50) implied for the IDV spine and for the central GRB engine with the BZ mechanism that couples to the black hole horizon itself. Normally expected to generate only a fraction of the energy output of the other disk mechanisms [10], the BZ process nevertheless could *appear* to dominate in observations where beaming angles are extremely small.

The identification of mechanisms like the PC/BP and BZ ones as being responsible for most of the AGN jets observed brings up an important fourth point. Black holes with similar mass and accretion rate can differ in radio power by several orders of magnitude. *Jet production mechanisms that depend on extraction of black hole rotational energy, therefore, provide a third parameter that lifts the mass/accretion rate degeneracy and potentially can explain why some sources are radio loud and some are radio quiet* [22,13]. Such mechanisms have jet powers that vary significantly with the normalized black hole spin $j \equiv J/(GM^2/c)$ but still vary linearly with the accretion rate and mass (see Figure 1)

$$L_{jet} = L_{Edd}\ \ (\dot{M}/\dot{M}_{Edd})\ \ j^2 \tag{1}$$

1.4. The Important Role of Accretion and a Toy Model

Because the type of jet produced in black hole systems appears related to the structure of the accretion flow (low/hard, high/soft, *etc.*), this brings me to my fifth point. *It is no longer reasonable to consider accretion models without also considering jet production.* Unfortunately, none of the current accretion models address jet production in any meaningful way. This point is emphasized by the association of jet production with the presence of quasi-periodic oscillations in the X-ray light and with 'dips' in the X-ray emission at essentially the same time as the jet is ejected. The latter occurs not only in Microquasars like GRS 1915+105 but also in Macroquasars like 3C 120 [12]. In short, it is not clear that we have an adequate accretion model that will begin to address one of the more important aspects of all accreting sources — jets.

I therefore propose the following toy scenario, whose main purpose is to stimulate further thinking along these lines. The sheath is produced in the accretion disk in low $\dot{M}$ states (*i.e.*, low/hard state and in X-ray dips in the very high/unstable state). It can have Lorentz factors up to 10 or more, so it is produced probably near the ergosphere. It dominates in low-luminosity sources (FR Is, low-luminosity AGN, and persistent X-ray binary jets). The low/hard power-law tail in Cyg X-1 may originate in the sheath.

The spine, on the other hand, is produced only in high $\dot{M}$ states, when rapid accretion can press the magnetic field onto the black hole (high/soft state and between dips in the very high/unstable state). It can have Lorentz factors up to 50 and higher, so it is produced probably very near the horizon. The spine is more important in high-luminosity sources (FR IIs, GRBs, and high-luminosity X-ray transients). In Cyg X-1 the hard MeV tail in the high/soft state may originate in this jet.

2. Jet Collimation, Acceleration, and Stability

2.1. Collimation

As pointed out in [15], there are both theoretical and observational reasons for concluding that slow acceleration and collimation is probably the norm for jet outflows in these sources. Nonrelativistic [9] and relativistic [20] models of MHD wind outflows attain solutions where the wind opening angle is wide near the accretion disk and then narrows slowly over several orders of magnitude in distance from the disk. Furthermore, recent observations of M87, for example, by [7] suggest that the opening angle of the jet is more than 60 deg at the base, collimating to a few degrees only after a few hundred Schwarzschild radii. Furthermore, the lack of significant 'Sikora' bump in the X-ray light of most radio quasars indicates that the flow at the base of most quasar jets must also be broad and probably sub-relativistic, only accelerating to relativistic flow much further from the black hole.

These observational results have important implications for the spine/sheath model. If there is, indeed, a BZ-type high-Γ jet produced near the black hole, then this jet nevertheless cannot dominate in even the most powerful of radio quasars. Such a flow would intercept the soft photons from the accretion disk, Compton-scatter them to hard X-ray energies, and produce a substantial Sikora bump. The lower Lorentz factor flow, collimated and accelerated slowly, must still dominate in even the brightest of radio quasars. This conclusion is consistent with the observation that the parsec-scale jets in both FR I and FR II radio sources appear to have similar structures and speeds [6].

2.2. Attaining Relativistic Speeds: Poynting Flux-Dominated Jets

It is important to realize that, if an MHD/ED mechanism for jet acceleration is adopted, then this implies that (at least initially) the jets so-produced must be Poynting flux-dominated (PFD). By definition, $\Gamma >> 1$ implies that the kinetic energy greatly exceeds the rest mass-energy of the flow. And, for an MHD jet, the final velocity is at least of order the Alfven speed, so the Alfven Lorentz factor also must be large: $\Gamma_A = V_A/c = B/(4\pi\rho c^2)^{1/2} >> 1$. That is, the field lines must have low mass-loading, and the energy flow must be dominated by the flow of electromagnetic energy (Poynting flux), not kinetic energy. As the flow accelerates, Poynting flux is slowly converted into kinetic energy flux, until the two are of the same order of magnitude [20,21]. Eventually, mass entrainment from the interstellar medium can increase the baryon loading, decreasing the Poynting flux domination.

2.3. Stability of Poynting Flows

So far no fully relativistic numerical simulations of PFD flows have been performed. The best results to date are from three-dimensional *non-relativistic* simulations [16,17]. We find that the stability is critically dependent on how severe the mass entrainment in the jet is — specifically on the *gradient* of the plasma parameter $\beta \equiv p_{gas}/(B^2/8\pi)$. (In the following, remember that β is always less than unity for PFD jets, if the plasma is reasonably cold $P \leq \rho c^2$.) If β decreases or remains small as the jet propagates outward (mass loading becomes even less or stays the same), then we find that the PFD jet remains stable. However, if β *increases* (entrains significantly more thermal material), then we find that the jet is likely to be unstable to the helical kink instability, *even if the jet still remains magnetically dominated throughout the simulation.* Apparently even a small amount of pressure in the flow builds up over large distances, triggering a helical kink and, therefore, turbulence in the jet.

We tentatively suggest that this may be part of the reason why FR II sources appear only in elliptical galaxies. The presence of a high gas density in spiral galaxies may allow the entrainment of relatively more matter than in ellipticals, especially if the propagation direction of the jet makes a small angle to the plane of the spiral disk. While active ellipticals do have a substantial amount of gas, that material will generally be in a disk about the active nucleus with a rotation axis more or less aligned with the central black hole and, therefore, the jet.

3. Conclusions

In the review above I have emphasized several important points in the study of relativistic jets:

1. High energy jet sources of all types should be considered when attempting to understand relativistic jets. Micro- and Macroquasars both provide important clues to the mechanisms at work.

2. There are observational reasons for believing that the same source may produce jets of rather different Lorentz factors, either simultaneously or in different accretion states. This may lead to a spine/sheath jet structure.

3. Similarly, there are natural theoretical reasons for believing that more than one MHD/ED jet launching mechanism may be at work in a give black hole engine, and there are candidates for both spine and sheath.

4. Some jet production mechanisms at work near the black hole rely on the extraction of black hole rotational energy. This provides a third parameter, in addition to black hole mass and accretion rate, that potentially can explain why sources with similar optical appearance are radio loud and some are radio quiet.

5. It is no longer reasonable to consider accretion models without also considering jet production as an integral part of the accretion process. Many, if not all, sources produce jets, and it is clear that the production of a jet is affected by, and can affect, the structure of the accretion flow.

6. Slow acceleration and collimation appears to be the norm, both from observational and theoretical investigations.

7. By nature, relativistic jets that are launched via MHD/ED processes will be Poynting-flux dominated (PFD).

8. PFD jets remain stable as long as they do not entrain a significant amount of thermal material, or if they become even more magnetically dominated. However, if there is a significant amount of entrainment of hot plasma, such that the plasma β has a positive gradient, then the jet is may be subject to the helical kink instability.

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